

APPLICATION
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TITLE: SYSTEM AND APPARATUS FOR HEAT REMOVAL

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SYSTEM AND APPARATUS FOR HEAT REMOVAL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/448,951, filed on February 19, 2003, which is incorporated by reference herein.

BACKGROUND

5 This invention relates to heat transfer.

 With continuing advances in electronics and especially computer electronics, electronic devices are getting smaller, faster, and hotter. Advances in the manufacture and design of computer chips (CPUs) have, for example, resulted in denser chips and dramatic increases in processing speed, as well as increased production of heat. Advances
10 in the design and use of graphics cards (and other PC cards or boards) have resulted in more detailed simulation graphics that can be shown in real time, as well as increased production of heat. Similarly, advances in hard disk technology have resulted in storage of more data with rapid access, as well as increased production of heat.

 Heat jeopardizes the performance and viability of electronic devices. For
15 example, as the temperatures of CPUs rise, failure rates increase dramatically. In an encased electronic device, for example a conventional computer, the heat produced by electronic devices, for example CPUs and PC cards, can readily accumulate and rise to dangerous levels. Such accumulation is exacerbated when there are multiple heat-producing elements, especially if they are clustered near one another, and when the
20 electronic device is small. Under these circumstances – with the production of more heat in a smaller encased space – heat is less readily dissipated away from the heat-producing electronic devices.

 To ensure the proper and long-term functioning of encased electronic devices, heat must be removed. Conventional computers remove the heat produced inside an
25 encased computer with fans. The fans can be situated inside the computer, and can circulate air through vents in the computer casing, thus cooling the components inside. In addition, heat sinks can be mounted to electronic components inside an encased electronic device.

SUMMARY

The invention provides systems and apparatus for removing heat from an encased electronic device.

In general, in one aspect, the system includes a thermal ground, one or more
5 conduction pathways that thermally couple one or more heat-producing elements of an encased electronic device to the thermal ground so that the thermal ground receives heat produced by the heat-producing elements, and a heat dissipation element that is thermally coupled to the thermal ground and configured to transfer heat from the thermal ground to an environment external to the encased electronic device. The conduction pathways and
10 the heat dissipation element provide a capacity to remove heat from the encased electronic device such that heat removal by convection from the heat-producing elements is not required.

Particular implementations can include one or more of the following features. The system can be configured so that the use of a fan is not required to remove heat from the
15 encased electronic device. The encased electronic device can include a plurality of heat-producing elements; the one or more conduction pathways can thermally couple the plurality of heat-producing elements to the thermal ground; and the heat removal system can require only one heat dissipation element to remove from the encased electronic device heat produced by the plurality of heat-producing elements.

20 The electronic device can be a computer encased in a thermally conductive casing. The heat-producing elements of the computer can include any combination of a central processing unit, one or more PC cards, one or more disk drives, and one or more power supplies. The thermal ground can be a thermally conductive plate situated inside the encased computer and the heat dissipation element can include the thermally
25 conductive casing of the computer.

The thermal ground and the heat dissipation element can be integrated. The thermal ground can provide structural support. The thermal ground can be a plate, a rod, a sphere, a pyramid, or a block. The thermal ground can be made of any combination of aluminum, copper, anisotropic graphite fiber composites, and nano-tube graphite. The
30 thermal ground can include active thermionic elements.

The heat dissipation element can be configured to remove heat from the thermal ground by any combination of natural convection, forced convection, conduction, and radiation. The heat dissipation element can include features situated and configured to dissipate heat by natural convection to the environment external to the encased electronic device. The features can include fins. The heat dissipation element can include a conduit thermally coupled to the thermal ground and through which a coolant can flow.

At least one of the one or more conduction pathways can be provided by a thermal connector. The system can include an insulation casing configured to attach to at least one of the heat-producing elements and reduce heat transfer by convection from the at least one heat-producing element to the environment inside the encased electronic device.

The invention can be implemented to realize one or more of the following advantages, alone or in various possible combinations. Heat can be removed from a computer without the use of fans. Heat can be removed from a computer with little noise or in silence. Heat can be removed without the vibrations, electromagnetic noise, or mechanical resonance caused by fans. The variability of magnetic and electric fields in the computer can be reduced. Maintenance issues created by the use of fans can be reduced or eliminated. Mechanical fatigue of computer components can be reduced. The circulation of air into a computer is not necessary. The computer can be sealed. The computer can exclude moisture, and can be operated in moist or chemically adverse environments. Maintenance issues created by entry into a computer of dust, ions, debris, airborne chemicals, and contaminants can be minimized or eliminated. The computer can be protected from external electric, magnetic and electromagnetic fields. Performance of the computer can be improved. The lifespan and reliability of the computer can be improved. One implementation includes all of the above described advantages.

The details of one or more implementations of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a diagram of a system for removing heat from a computer according to one aspect of the invention.

5 FIG. 2 illustrates a system for removing heat from a computer according to one aspect of the invention.

FIG. 3 illustrates components of a system for removing heat from a computer, including a heat dissipation element, thermal ground, thermal connector, and a CPU mounted on a circuit board.

10 FIG. 4 shows a thermal connector having two parts but kept under pressure by springs.

FIGS. 5A-C each illustrates a thermal connector for thermally coupling a PC card to a thermal ground according to one aspect of the invention.

FIGS. 6A-E each illustrates a thermally conductive bridge having two connectable segments according to one aspect of the invention.

15 FIG. 7 illustrates a disk drive covered by a thermally conductive elastomer and coupled to a thermal ground in the shape of a plate by direct contact leaving the connecting ribbons free to connect as needed according to one aspect of the invention.

FIGS. 8A-C each illustrates a disk drive covered by an elastomer according to one aspect of the invention.

20 FIGS. 9A-B each illustrates a disk drive covered by an elastomer and thermally coupled to a thermal ground according to one aspect of the invention.

FIGS. 10A-B are diagrams indicating the path of heat flow for one aspect of the invention, as used in a mathematical thermal model.

25 FIG. 11 is a diagram indicating placement of thermal sensors in one implementation of the invention.

FIGS. 12A-D are graphs showing temperature as a function of time at various locations during operation of one implementation of the invention.

30 FIGS. 13A-B are graphs showing temperature and thermal resistance, respectively, of the heat dissipation element in one implementation of the invention, as a function of the power that is being dissipated with natural convection.

FIGS. 14A-B are graphs showing temperature and thermal resistance, respectively, of the heat dissipation element in one implementation of the invention, as a function of the power that is being dissipated with forced convection.

Like reference symbols in the various drawings indicate like elements.

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DETAILED DESCRIPTION

The invention provides systems and apparatus for removing heat from an encased electronic device. A heat dissipation element dissipates, to an environment external to a casing of the electronic device, heat that is produced by exothermic or heat-producing elements of the electronic device, for example, a CPU, one or more PC cards, a disk drive, and a power supply. Each of one or more such heat-producing elements is thermally coupled to a thermal ground. The thermal ground can be any shape, for example, a plate, rod, block, sphere, pyramid, or block. In one implementation, the thermal ground can be the casing of the electronic device. The thermal ground receives heat produced by the devices and transfers it to the heat dissipation element. In one implementation, the system includes a common thermal ground for all of the heat-producing elements. The heat dissipation element then dissipates the heat into the environment external to the casing. In one implementation, the thermal ground and heat-dissipating element are integrated as one element.

FIG. 1 shows a system in accordance with the invention for removing heat from an encased electronic device, which can be, for example, a computer. The system for removing heat 100 includes one or more conduction pathways, a heat dissipation element 106, and a thermal ground 110. The ground 110 is thermally coupled to the heat dissipation element 106, for example, by direct contact as shown. The ground 110 and the heat dissipation element 106 can be a part of a casing 105, and the ground can be structurally supportive for one or more heat-producing elements. The casing 105 encloses one or more heat-producing elements, for example, a CPU 120 on a circuit board, PC card 121, disk drive 122, and a power supply 123. Each heat-producing element is thermally coupled to the ground 110, forming a conduction pathway. For example, a CPU 120 can be thermally coupled to the ground 110 by a thermal connector 130, a PC card can be thermally coupled to the ground 110 by a detachable thermal connector 131,

a disk drive 122 can be thermally coupled to the ground 110 by a thermal connector 132 that pierces an insulator 140 around the disk drive, and a power supply 123 can be thermally coupled to the ground 110 by direct contact 133. The thermal connectors and direct contact (in the case of the power supply) can provide a conduction pathway through which heat can move from the heat-producing elements to the thermal ground. In the present specification, the term conduction pathway refers to any pathway through which heat can move by conduction. A conduction pathway between a heat-producing element and the thermal ground can be formed, for example, by one or more thermal connectors and/or one or more thermal plugs. A thermal connector (also referred to as a thermal bridge or a thermally conductive bridge) can have various size and shape. Examples of thermal connectors are provided below.

The thermal connectors can be flexible cables of any combination of the following: carbon fibers, fibers made of carbon nano tubes, diamond and other fibers with high thermal conductivity are coated with silver, gold, copper, aluminum and other metals/materials or diamond along the linear surface of the fibers, group of fibers, ribbons or tapes. The coated fibers, ribbons or tapes can be bundled and fused/sintered to create a linear/tubular matrix of highly conductive material with the coating of other highly conductive material. Maximum compacting can be achieved by the fuse/sinter process or, alternatively, compacting can be reduced to provide flexibility as appropriate. The bundle can become a single integrated structure. In addition, the two end lateral surfaces can be plated with the same material used for fusing the fiber. In this plating process, high thermal conductivity is achieved for the complete bundle and also the interface between the bundle and the thermal ground. The thermal ground can also have a plating of the same metal/material to provide interface between same material to achieve the lowest thermal resistance. The above described processes can be used for making all components of the heat removal system.

The thermal ground 110 can receive heat from each of several multiple heat-producing elements 120-123, directly or through one or more thermal connectors. The thermal ground 110 is made of a thermally conductive material, for example, copper or aluminum. Other thermally conductive materials can be used. The ground can be fabricated from plate, rod, or block form materials and can be a composite of several

different materials, including anisotropic graphite fiber composites, carbon fiber composites, nano-tube graphite, and carbon nano-tubes. The ground 110 may serve as a supportive structure for all elements of the encased electronic device, and can have a large face relative to the size of the heat-producing elements or multiple surfaces so that it can be coupled to and accumulate heat from several heat-producing elements. In one implementation, the thermal ground is the main structure for mounting all electronic components of the encased electronic device. The thermal ground 110 is similar to an electrical ground in that it is conductive and provides a single common base for absorbing energy. The thermal ground provides a single avenue through which heat from the heat-producing elements 120-123 is transferred to the heat dissipation element 106.

The thermal ground 110 when used as an enclosure can shield the computer components from electromagnetic energy, and can protect from lower RFI frequencies than a standard computer casing. The ground can also prevent electrostatic potentials. Electrostatic potentials can be created by electromagnetic fields from large motors, radiating antennas, or diathermy devices near the computer. Electrostatic potentials also can be created by varying signal potentials occurring at different chip-sites within the computer.

The heat dissipation element 106 receives heat from the thermal ground and dissipates it outside of the encased electronic device. The heat dissipation element 106 is made of a thermally conductive material, for example, copper or aluminum. The heat dissipation element can include additional cooling elements, for example, active thermionic elements, heat pipes, or fluid chiller. The heat can be dissipated by conduction, for example, to a fluid (e.g., a coolant) circulating through conduits (e.g., tubes) that are thermally coupled to the thermal ground. Heat can also be dissipated by radiation from the encased electronic device and the heat dissipation element 106.

The heat dissipation element 106 provides a large surface area for convective dissipation of heat into the environment. The heat dissipation element can have externally projecting features shaped like fins, blades, rudders, sheets, or the like. Optionally, the heat dissipation element can include a hairy heat exchanger. In one implementation, the hairy heat exchanger is made from thermally conductive and flexible fibers. One end of the bundle is thermally coupled to the thermal ground. The other end of the bundle

extends to the environment external to the encased electronic device and, furthermore, can be free floating (not attached to each other or to another structure) so that the fibers at the free floating end can be moved by natural convection. The hairy heat exchanger is further described in commonly owned U.S. Provisional Application entitled “High Efficiency Silent Solid State Thermal Management System – SSTM”, filed on October 22, 2003, the listed inventor of which are Alfred Zinn, John Sokol, Allen Amaro, Harrison Rose, and Fred Zeise.

The degree of heat dissipated by convection can be adjusted by changing the shape or size of the heat dissipation element. For example, increasing the surface area of the externally projecting features without changing their volume typically increases the degree of heat dissipated by convection.

The heat can be dissipated from the heat dissipation element 106 by passive convection, for example, due to naturally occurring air movement external to the computer. The heat also can be dissipated from the heat dissipation element 106 by forced convection, for example, air movements created by external fans and/or coolant being pumped through conduits (e.g., tubes) thermally coupled to the thermal ground.

The configuration of the system can be varied depending on the heat removal requirements of the encased electronic device. For example, the thermal connectors that provide conduction pathways can be made of more conductive materials, shortened, and/or have increased cross sectional area when the heat removal requirements increased.

FIG. 2 illustrates a system 200 for removing heat from a computer without the use of fans or vents according to one implementation of the invention. The system 200 for removing heat includes a casing 205 and a heat dissipation element on the outside of the casing 206. The heat dissipation element can have features for dissipation of heat, for example, parallel projecting planar segments each having two or more faces exposed to the air, as shown in FIG. 2. The heat dissipation element can include one or more components and can be present on one, all, or any number of sides of the computer, for example, four sides of the computer as shown in FIG. 2. A portion 207 of the casing 205 can be removed to provide access to the interior of the computer 200 and replaced to re-establish the encased computer. The system 200 for removing heat includes a thermal

ground 210 that forms part of the casing 205 and upon which components of the computer can be mounted.

A printed circuit board 215 can be mounted to the thermal ground 210 so that the circuit board 215 faces the ground – that is, so that components mounted to the board face, for example a CPU 220, are sandwiched between the motherboard and the ground rather than being exposed to the interior of the computer. The circuit board 215 can be fastened to the ground 110 with spacers 212 to prevent contact between components on the circuit board 215 and the ground 210. A heat-producing component on the circuit board 215, for example the CPU 220, can be thermally coupled to the ground 210 by a thermal connector 230, discussed in more detail below.

A PC card 221 can be electrically attached to an electrical connector 222 on the backside of the circuit board 215 and coupled to the ground 210 by a thermal connector 231 that extends around the edge of the circuit board 215, as shown, or through a hole in the circuit board 215. A PC card includes any type of card that is connectable to an expansion slot, for example, a PCI, ISA, AGP, or VME slot. The thermal connector 231 can be a thermal strap, for example, a heat pipe or copper rod around or through the circuit board, and passes heat from the PC card to the thermal ground 210.

An exploded view of a system for removing heat from a heat-producing element, according to another aspect of the invention, is shown in FIG. 3. A heat-producing element, for example, a CPU 320, can be mounted on a circuit board 315 and can be thermally coupled to a thermal ground 310 with a thermal connector 330. The board 315 can be fastened to the ground 311, for example, with pins attaching each of one or more connectors 301 on the board to each of one or more connectors 311 on the ground 310 so that the thermal connector 330 is held tight against the CPU 320 and the ground 311. The ground 310 is thermally coupled to the heat dissipation element 306. The heat dissipation element 306 can have externally projecting features that form a series of projecting prism-shaped segments, each segment exposing two rectangular faces to air outside the computer. The heat dissipation element 306 can include conduits 340 for the circulation of fluid through the heat dissipation element 306.

The thermal ground 110, 210, 310 can be coupled to a heat-producing element, for example, a CPU 120, 220, 320, PC card, 121, 221, disk drive 122, or power supply

123, with a thermal connector 400 that includes two or more joined segments 410, 420, as shown in FIG. 4. Each segment 410, 420 of the thermal connector 400 can move relative to the other 420, 410 while maintaining contact between the segments 410, 420. For example, a top segment 420 can slide up the slanted face of a bottom segment 410 so that the two segments 410, 420 form a cylinder. The segments can be held against each other with a spring 430 attached to each segment and crossing the plane of contact between the segments. In the implementation shown in FIG. 4, the thermal connector 400 can move with three degrees of freedom and can adjust for differences in the distance, parallelism and contact pressure between a heat-producing element, for example, a CPU 120, 220, 320, and the thermal ground 110, 210, 310. This movement of the two or more joined segments maintains thermal coupling between the heat-producing element, for example, a CPU 120, 220, 320, and the thermal ground 110, 210, 310 if, for example, the ground expands and contracts due to changes in its temperature.

A heat-producing electronic device, for example, a PC card 121, 221, can be thermally coupled to a thermal ground 130, 230 with a combined thermal and electrical interface as shown in FIGS. 5A-C. A PC card 521, 571 has an electrical connector portion 522, 572 that can be inserted into an electrical slot or plug 532, 582 on a circuit board 515, 565. The PC card 521, 571 can also have a thermal connector 523, 573 that is secured and thermally connected to the PC card 521, 571 and which can be coupled to a thermal ground 510, 560.

As shown in FIGS. 5A-B, the thermal connector 523 can include a wedge-shaped extension insertable into a thermal plug 533 that is secured and thermally connected to the thermal ground 510. The thermal connector 523 and thermal plug 533 are made of thermally conductive material. As shown in FIG. 5C, the thermal connector 573 can be a small rod (e.g., 1/4" diameter) that extends through the circuit board 565 and inserts into a socket 583 in the thermal ground 560. The socket can be a simple hole (e.g., 1/4" diameter and 3/8" deep) in the thermal ground 560. The thermal connector 523, 573 and receptacle plug 533 or socket 583 permit easy insertion and removal of the PC card from the circuit board 565.

When the thermal connector 523, 573 is connected to the thermal ground 510, 560, either directly into a socket 583 or by way of the thermal plug 533, a conduction

pathway is created. The conduction pathway can conduct heat from the PC card 521, 571 to the thermal ground 510, 560. As shown in FIG. 5C, electrical plugs 532, 582 and corresponding thermal plugs or sockets 533, 583 for two or more PC cards 571 can be placed close together on the circuit board 515, 565, because heat is removed from the PC cards through the conduction pathway rather than dissipating into the air inside the computer, thereby potentially reducing the required size of the computer.

In general, a conduction pathway can be provided by two or more connectable segments, where one segment is thermally connected to a heat-producing element and a connectable segment is thermally connected to or included in the thermal ground. As shown in FIGS. 6A-E, the connectable segments can be shaped in many different ways. Typically, the connectable segments interconnect on multiple planar or cylindrical surfaces to maximize the rate of heat transferred from one segment to the other.

Convective heat losses from heat-producing components can be reduced and heat-producing components that have moving parts, for example, a disk drive, can be silenced and protected from mechanical vibrations as well as chemical or other contamination (e.g., water), while still providing an avenue for heat removal, by surrounding them with a flexible elastomer material or shock-absorbing foam while maintaining a conduction pathway between the component and a thermal ground. In this way, the component is insulated from vibration, but heat flows from the component to the thermal ground.

The components can be coated with a nonremovable elastomer, or surrounded with a removable elastomeric jacket. The elastomer can be polyalkylene, polyurethane, silicone rubber or any other solid elastic material with a thermal conductivity from around 0.05 W/mK or better (where K is degrees Kelvin). For a 12-watt disk drive, a conductivity of about 1 W/mK is preferred. The elastomer can be filled with metal, carbon fibers, graphite pitch, or carbon black to increase thermal conductivity. The elastomer can be filled with glass spheres or talc to increase the acoustic absorption and attenuation. Multiple layers of elastomer can be used. For example, a layer of firm rubber can cover a component, for example a disk drive, and a layer of less firm rubber can surround the layer of firm rubber.

As shown in FIGS. 7 and 8A, a disk drive 722 can be surrounded on all sides by an elastomer 740. The elastomer absorbs noise produced by the disk drive and mechanical shocks from outside the computer, and can prevent chemicals from reaching the disk drive. Cables 732 can extend through the elastomer to electrically connect the component to the rest of the computer. The disk drive 722 is thermally coupled to the thermal ground 710, which is a plate in the example shown. A disk drive can be thermally coupled to the thermal ground with, for example, a thermal strap, which can extend through the elastomer. A disk drive can be thermally coupled to the ground with a pin or screw, for example, screw 932 (FIG. 9A) which can extend from the thermal ground 910, through the elastomer 940, and into the disk drive 922. A disk drive can be thermally coupled to the thermal ground by, for example, direct contact on one side and surrounded by elastomer on the remaining sides. FIG. 8B shows an example of this implementation. The disk drive 822 is thermally coupled to the thermal ground 810 by direct contact on one side and surrounded by elastomer 840 on the remaining sides. In this implementation, the connecting ribbons can be connected as needed.

The use of screws to thermally couple a disk drive to a thermal ground can expose the disk drive to mechanical vibrations and may provide a path for emission of noise. As shown in FIG. 8C, a high thermal conductor, for example, solid rubber 851, can be placed between the disk drive 822 and the thermal ground 810, and a good acoustic absorber, for example, a foam rubber 841, can surround the remaining sides. A second ground 843 can be placed over the foam 841 and secured to the thermal ground 810 with pins or screws 850 that pierce the layer of rubber 851 to fasten the disk drive 822 to the ground 810. Alternatively, the disk drive 922 can be fastened to the thermal ground 910 with one or more straps 950 that extend over or through the elastomer coated disk drive 922 and are secured to the ground 910, as shown in FIG. 9B.

The invention does not require the removal of hot air from inside a computer. Hot air may be produced inside the computer by the convective dissipation of heat directly from the heat-producing elements. Hot air can be removed, for example, with fans inside the computer that move hot air away from the heat-producing elements and vents that allow the air to circulate in and out of the computer.

Reliance on fans can affect performance and may jeopardize the viability of the computer. For example, the efficiency of a fan usually decreases as the result of normal mechanical wear, which can increase the heat produced by the fan and decrease the air flow. The efficiency of fans also decreases due to the accumulation of dust and other contaminants, which reduces air flow and hence cooling produced by the fan, and which may create moving electrostatic fields adversely affecting the performance of nearby electronic devices. Fans also generate internal mechanical resonance with harmonic vibrations that can affect performance, for example, of hard drives. If a fan fails, a computer may overheat and be irreparably damaged. Even if the computer is undamaged, it must be opened for maintenance of the fans, which risks accidental damage to other components.

The above described system removes heat produced inside a computer without reliance on convective dissipation inside the computer and subsequent removal of the resulting hot air by fans. The system conducts heat to a heat dissipation element outside the computer, which transfers or dissipates the heat outside the computer. Thus, the system can remove heat from a computer without the noise that fans produce – that is, the computer can be operated in silence. The system also can remove heat from a computer that does not have vents, including a computer that is sealed to minimize or prevent the entry of air, water, and/or contaminants into it.

A mathematical thermal model was developed to demonstrate the effective removal of heat from an encased electronic device in one implementation of the invention. As shown in FIGS. 10A-B, the model is for heat that flows from a CPU 1020 across an interface to a thermal connector (“cylinder”) 1030, then across an interface to a thermal ground 1010, then across an interface to a heat dissipation element and finally into the environment. The physical properties and parameters used in the mathematical model are given below in Table 1.

Table 1.

Thermal Conductivity	Area	Heat Path Length
$K_{alum} := 240 \frac{W}{m \cdot K}$	$A_{cpu} := 0.0015 m^2$	$L_{paste} := 2.54 \cdot 10^{-5} m$

$A_{cpu} := 0.0015m$		
$K_{cyl} := 240 \frac{W}{m \cdot K}$	$A_{cyl} := 0.002m^2$ $A_{cyl} := 0.002m$	$L_{cyl} := 0.0254m$
$K_{plate} := 240 \frac{W}{m \cdot K}$	$A_{plate} := 0.154m^2$	$L_{platehtsnk} := 0.017m$
$K_{thermgrease} := 1 \frac{W}{m \cdot K}$		

In the mathematical thermal model, conductive heat flow is one-dimensional and steady state, and criteria are defined as follows. The CPU has a power dissipation of 75 watts. The thermal connector is centered on the thermal ground. Thermal coupling grease at a thickness of about 1.0 mm is considered to be used at interfaces between components. The thermal ground is an integral part of the casing. Heat is dissipated by the heat dissipation element by natural convection. Heat produced by a power supply, PC cards, and disk drives is not part of the model.

The model describes the thermal conductivity for each device in the heat flow path as a parameter K_{device} , where K is degrees Kelvin. The basic thermal resistor for one-dimensional steady-state conduction heat flow for each device is then

$$R_{device} := \frac{\text{Length}}{\text{Area} \cdot K_{device}} \quad \text{Where:} \quad K_{device} = \frac{\text{Watts}}{\text{meter} \cdot \text{Kelvin}}$$

such that the units for R_{device} are

$$R_{devices} := \frac{s^3 \cdot K}{kg \cdot m^2}$$

The following linear thermal resistances were calculated based on resistance of materials and dimensions of the relevant component or feature. The first contact resistance R_{cpucyl} for the interface between the CPU 1020 and the thermal connector is

$$R_{cpucyl} = 0.017 \frac{s^3 K}{kg m^2}$$

The thermal resistance R_{cyl} of the thermal connector is

$$R_{cyl} = 0.053 \frac{s^3 K}{kg m^2}$$

The contact resistance R_{cylplate} for the interface between the thermal connector 1030 and the thermal ground 1010 is

$$R_{\text{cylplate}} = 0.013 \frac{\text{s}^3 \text{K}}{\text{kg m}^2}$$

The thermal resistance R_{spreader} of the thermal ground 1010 is

$$R_{\text{spreader}} = 0.084 \frac{\text{s}^3 \text{K}}{\text{kg m}^2}$$

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The contact resistance $R_{\text{platehtsnk}}$ for the interface between the thermal ground 1010 and the heat dissipation element 1005 is:

$$R_{\text{platehtsnk}} = 1.649 \times 10^{-4} \frac{\text{s}^3 \text{K}}{\text{kg m}^2}$$

The total thermal resistance R_{heatsnk} for the interface between the heat dissipation element and ambient air is:

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$$R_{\text{heatsnk}} = 0.3 \frac{\text{s}^3 \text{K}}{\text{kg m}^2}$$

If the CPU is running at 100% with a power output Q of 75 Watts (W), the temperature drop ΔT across each resistance is given by $\Delta T = Q_{\text{cpu}} \times R_{\text{thermal}}$, where $Q_{\text{cpu}} = 75\text{W}$. The one-dimensional steady-state conduction model is represented by the equivalent thermal circuit that impedes the heat flow of the CPU's 75W of energy, as shown in FIG. 10B. The input is at the left and the heat is flowing passively through the computer, being dissipated by convection and radiation at the right. The sum ΔT_{total} of all the above thermal resistances in FIG. 10B is:

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$$\Delta T_{\text{total}} := \Delta T_{\text{cpucyl}} + \Delta T_{\text{cyl}} + \Delta T_{\text{cylplate}} + \Delta T_{\text{spreader}} + \Delta T_{\text{platehtsnk}} + \Delta T_{\text{heatsnk}}$$

20

$$= 1.27 + 3.969 + 0.953 + 6.308 + 0.012 + 22.5 = 35.011\text{K}$$

If the ambient temperature, T_{ambientC} , is 16°C , the absolute ambient temperature T_{ambient} is: $T_{\text{ambientK}} = T_{\text{ambientC}} + 273\text{K} = 289\text{K}$, and the temperature of the CPU is found

as $T_{\text{cpu}} = \Delta T_{\text{total}} + T_{\text{ambient}} = 324.011\text{K}$. Converting the CPU temperature T_{cpu} to degrees Celsius gives the theoretically calculated value of the CPU temperature as follows: $T_{\text{cpuC}} = T_{\text{cpu}} - 273\text{K} = 51.011^\circ\text{C}$. In comparison, the experimentally measured value of the CPU temperature is: 48°C . Thus, the theoretical thermal model is in reasonably close agreement with the experimentally measured values for CPU temperature.

The thermal model can be used to suggest improvements to the design of a system for removing heat from an encased electronic device according to the invention. For example, the model indicates that most of the thermal resistance in the system for heat removal is at the interface between the heat dissipation element and the air ($\Delta T = 22.5\text{K}$). If very low velocity air (4m/s or 750 linear feet per minute or LFM) is used to cool the heat dissipation element, the resistance of the heat dissipation element is lowered from 0.3 to $0.084\text{-s}^3 \cdot \text{K}/(\text{Watt})$. According to the model, the use of active external cooling results in a drop in CPU temperature from 51°C to 34.8°C , which is only 18.8°C above normal or ambient air temperature.

The results of a Flowmeric thermal simulation were consistent with the steady-state conductive thermal model described above. Temperatures measured on one implementation of the invention further demonstrate the effective removal of heat from an encased electronic device according to the invention, and also verify the theoretical thermal model and simulation described above.

Temperature measurements were taken at various locations on a prototype computer embodying the invention and having specifications as follows. The case is $4\frac{3}{4}$ inches in width, 17 inches in height and 14 inches in length. By comparison, the typical minitower computer case is 8 inches in width, 17.25 inches in height, and 19 inches in length. The thermal ground plate of the prototype has an area of 3,000 square inches and a thickness of less than 0.5 inches. The weight includes 27.5 Lbs of Aluminum and the total weight is about 32 Lbs. The electronic components include an Intel® D845GRG, a micro-ATX (9.60 inches by 8.20 inches), support for an Intel® Pentium® 4 processor in a $\mu\text{PGA}478$ socket with a 400/533 MHz system bus, an audio subsystem for AC '97 processing using the Analog Devices AD1981A, codec featuring SoundMAX Cadenza, Intel® Extreme Graphics controller, USB, 100 Megabits onboard Ethernet, low profile RAM of 256 Meg PC2100 DDR ram, an Intel P4 2.26 Gigahertz CPU with 533 Mhz

Front Side bus, a Fujitsu MPD3064AT 6 Meg disk drive. The power supply is 150 Watt ATX12V power compatible, with an input of 100 240 Vac, 47 63 Hz, 3 Amp and an output of +5 Vdc @ 26 A, 3.3 Vdc @ 8 A, -12 Vdc @ 1 A, +12 Vdc @ 6 A. There are no additional PCI or AGP slots. The form factor is a base-line 1U with overhead space requirements of approximately 3 inches. The box can be rack mounted allowing it to support any special usage, for example 3D visualization. The externally projecting features of the heat dissipation element are of length 16 inches and width 13.92 inches with a surface area of 3132.8 square inches and a weight of 24.8 lbs.

Temperatures were measured over time using a chronograph and a KRM meter with an internal electrical 0°C cold reference junction and type K Chromel-Alumel 10mm bead thermocouples. As shown in FIG. 11, measurements were taken on the system 1100 for removing heat at the following positions: on the CPU face 1101, at the thermal connector (i.e., the thermal bridge) 1102, at the heat dissipation element 1103, at the power supply 1104, at the hard disk 1105, and for air outside the computer.

As shown in FIGS. 12A and 12D, temperatures at all monitored locations in the computer rise rapidly when the CPU is put under full (100%) load. Under these conditions, the CPU has the highest temperature for the measured locations and the “CPU block” or thermal connector is the next hottest of the locations. As shown in FIGS. 12C and 12D, temperatures at all monitored locations in the computer drop rapidly when the CPU load ends. Thereafter, as shown also in FIG. 12B, the power supply and disk drives have the highest temperatures for the measured locations.

The relative effect of natural and forced convection on the temperature of the heat dissipation element is shown in FIGS. 13A-D. With natural convention, the temperature of the heat dissipation element rises to almost 40°C in 90 minutes, as shown in FIG. 13A, and the ratio of temperature to power falls to about 0.75, as shown in FIG. 13B. With forced convention, for the same system for removing heat, the temperature of the thermally conductive is reduced between 20°C and 7°C depending on the rate of air flow, as shown in FIG. 14A, and the ratio of temperature to power is reduced between 0.25 and 0.7, as shown in FIG. 14B.

A number of implementations of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the

spirit and scope of the invention. For example, the invention can be implemented to remove heat from industrial computers, desktop boxes (e.g., cable boxes), computer storage systems (e.g., SAN and NAS), telecommunication switching equipment, laptop computers, wireless base stations, supercomputers, clusters of computing devices, and home network central hubs. The above described features for isolating elements from vibrations can be implemented for any elements of the encased electronic device. Moreover, these features can provide isolation from vibration caused by any sources of vibration, including sources external and sources internal to the encased electronic device. Accordingly, other implementations are within the scope of the following claims.

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